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(54) **ON-TIME BASED PEAK CURRENT DENSITY RULE AND DESIGN METHOD**

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CPC ***G01R 19/04*** (2013.01)

(58) **Field of Classification Search**
USPC 702/64
See application file for complete search history.

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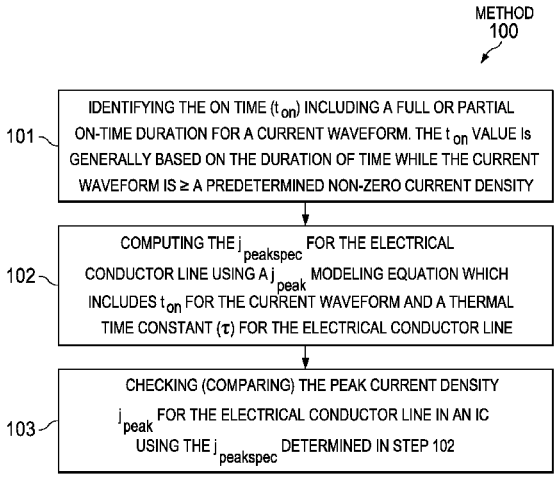
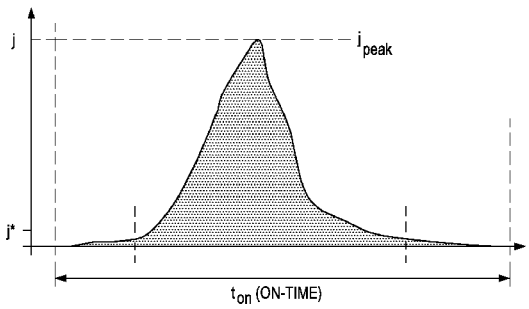
(57) **ABSTRACT**

A method of computing a peak current density specification ($j_{peakspec}$) for an electrical conductor line of an integrated circuit (IC) resulting from conducting pulsed electrical current represented as a current waveform. An on-time (t_{on}) is identified for the current waveform based on a current density being greater than or equal to (≥) a predetermined current density level. The $j_{peakspec}$ is computed for the electrical conductor line using a $j_{peakspec}$ modeling equation which includes the t_{on} for the current waveform and a thermal time constant (τ) for the electrical conductor line.

3 Claims, 3 Drawing Sheets





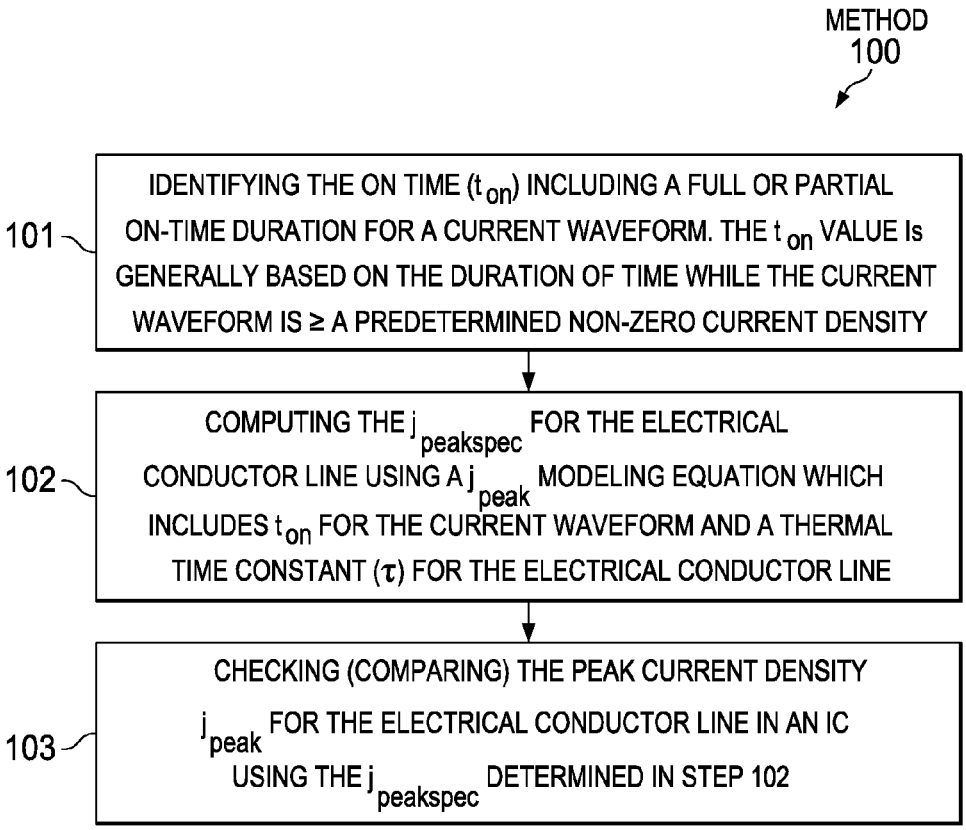

METHOD
100
101
IDENTIFYING THE ON TIME (t_{on}) INCLUDING A FULL OR PARTIAL ON-TIME DURATION FOR A CURRENT WAVEFORM. THE t_{on} VALUE Is GENERALLY BASED ON THE DURATION OF TIME WHILE THE CURRENT WAVEFORM IS ≥ A PREDETERMINED NON-ZERO CURRENT DENSITY
102
COMPUTING THE $j_{peakspec}$ FOR THE ELECTRICAL CONDUCTOR LINE USING A j_{peak} MODELING EQUATION WHICH INCLUDES t_{on} FOR THE CURRENT WAVEFORM AND A THERMAL TIME CONSTANT (τ) FOR THE ELECTRICAL CONDUCTOR LINE
103
CHECKING (COMPARING) THE PEAK CURRENT DENSITY j_{peak} FOR THE ELECTRICAL CONDUCTOR LINE IN AN IC USING THE $j_{peakspec}$ DETERMINED IN STEP 102

FIG. 1A

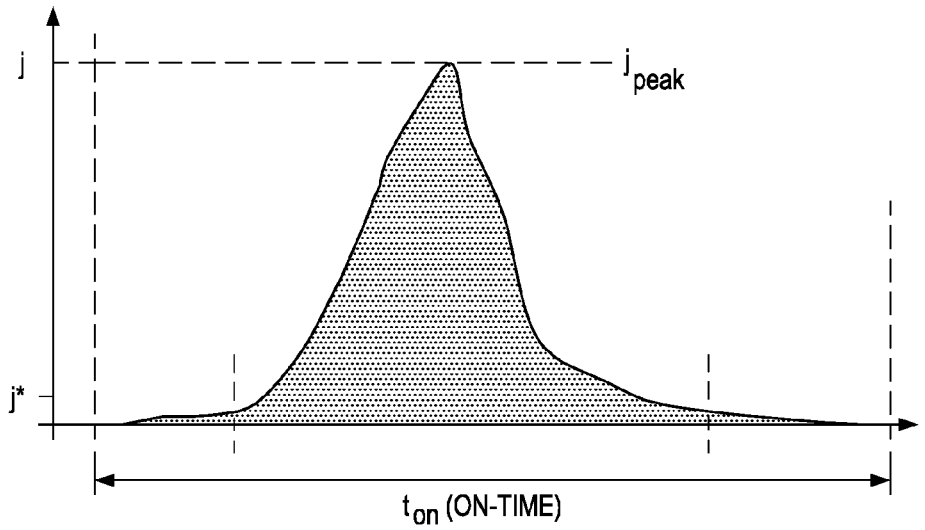

j
j_{peak}
j*
t_{on} (ON-TIME)

FIG. 1B

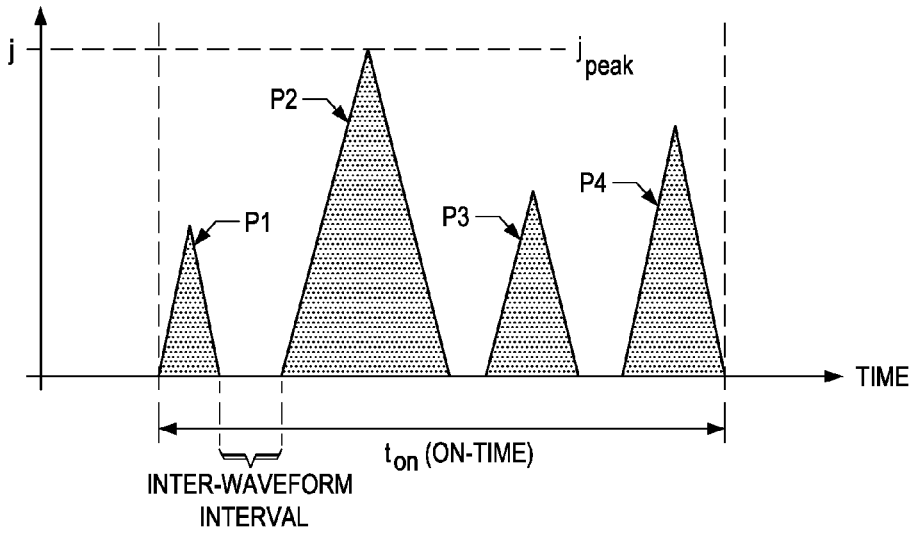

j
j_{peak}
P1
P2
P3
P4
TIME
t_{on} (ON-TIME)
INTER-WAVEFORM INTERVAL

FIG. 1C

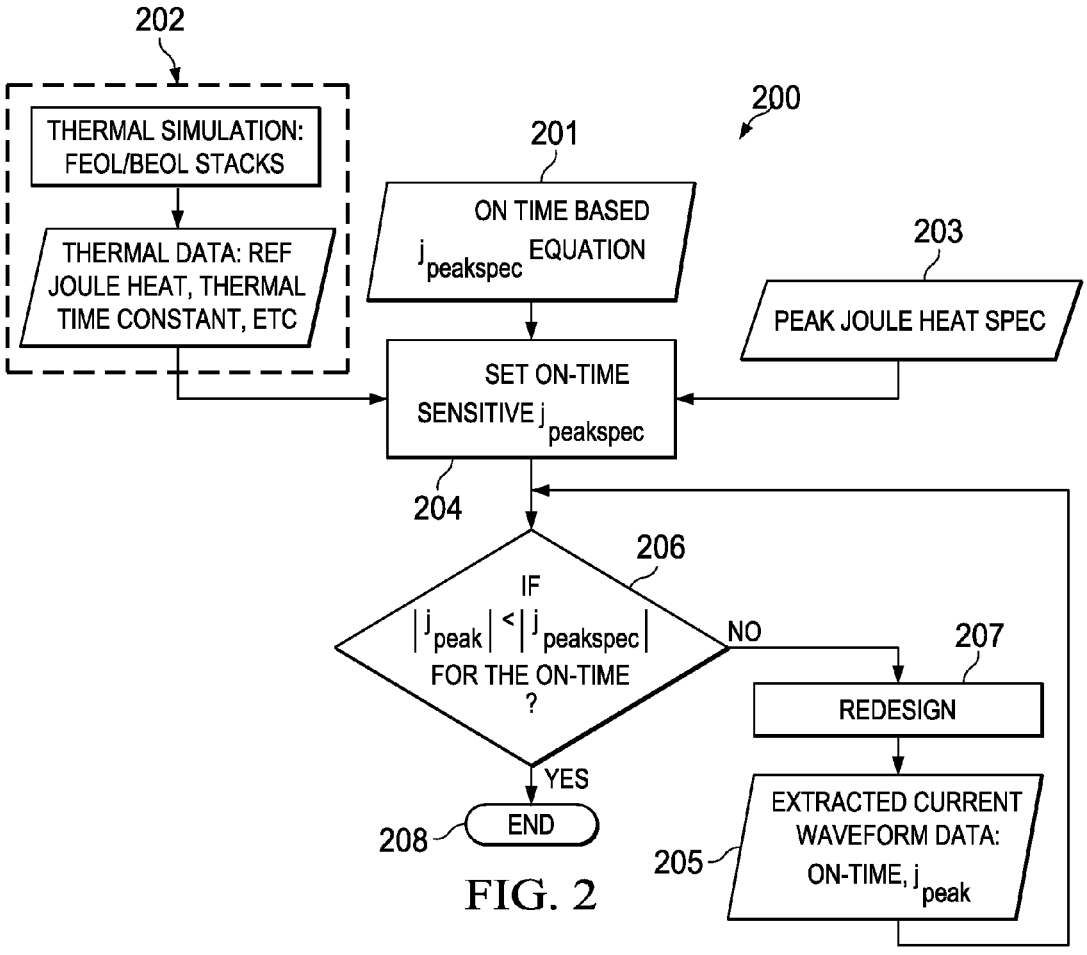

202
THERMAL SIMULATION: FEOL/BEOL STACKS
THERMAL DATA: REF JOULE HEAT, THERMAL TIME CONSTANT, ETC
200
201
ON TIME BASED $j_{peakspec}$ EQUATION
203
PEAK JOULE HEAT SPEC
SET ON-TIME SENSITIVE $j_{peakspec}$
204
206
IF $|j_{peak}| < |j_{peakspec}|$ FOR THE ON-TIME ?
NO
207
REDESIGN
YES
208
END
205
EXTRACTED CURRENT WAVEFORM DATA: ON-TIME, j_{peak}

FIG. 2

MODELED THERMAL PARAMETERS

$$j_{peakspec} = j_{rmsref}\left[\frac{dT_{spec}}{dT_{ref}}\ \frac{1}{\left[1\text{-}exp\left(-\frac{t_{on}}{\tau}\right)\right]}\right]^{\frac{1}{2}}$$

IN NORMALIZED MAGNITUDE

	τ (time unit)	j_{rmsref} (A/cm^2)	$dT_{ref}(C)$
M1	0.8	53.5	25
M2	2.5	36.2	25
M3	4.0	29.6	25
M4	7.0	25.7	25
M5	12.0	21.0	25

FIG. 3A

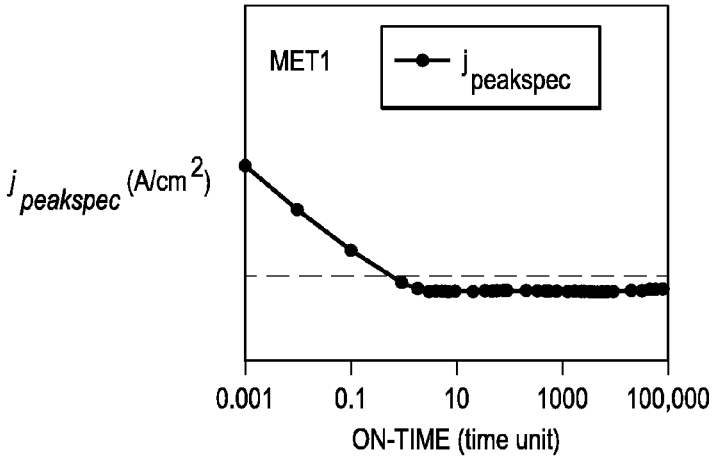


FIG. 3B

ON-TIME BASED PEAK CURRENT DENSITY RULE AND DESIGN METHOD

FIELD

Disclosed embodiments relate to reliability of integrated circuits, and more particularly to the peak current density parameter for electrical conductor (e.g., interconnect) lines on integrated circuits and design of integrated circuits.

BACKGROUND

Integrated circuits (ICs) are often designed to meet aggressive device density and circuit performance specifications. This trend has resulted in a reduction of the interconnect metal pitch and has increased the number of metallization levels. Aggressive interconnect scaling has increased current densities and associated thermal effects.

Thermal effects are an inherent aspect of electrical power distribution and signal transmission through the interconnects due to self-heating (or Joule heating) caused by resistance to the flow of electrical current. For a given process, circuit designers for IC designs using the process are provided maximum allowable values for three different interconnect current densities. These interconnect current densities are the average current density (javg), the root mean square (RMS) current density (jrms), and the peak current density (jpeak). The peak current density (j_{peak}) is simply the current density corresponding to the peak current level of the waveform, where the waveform refers to the visual shape (amplitude vs. time) resulting from pulsed electrical current through a conductor:

$$j_{peak} = \frac{I_{peak}}{A} \tag{1}$$

where A is the cross-sectional area of the interconnect or other electrical conductor line. Equation 1 does not consider the width of the pulse or the adjacent layers (e.g., dielectric layers) to the electrical conductor line which determines the thermal resistance reflected in a thermal time constant (τ) associated with the conductor line. Designing ICs to have a j_{peak} at or below an allowed j_{peak} limit (or j_{peak} specification) avoids unwanted melting failure in the IC. For example, if a given design results in a metal interconnect line having a $j_{peak} \geq a\ J_{peak}$ specification limit, the metal line widths may be increased to reduce the j_{peak}.

The average current density is defined as:

$$j_{avg} = \frac{1}{T}\int_0^T j(t)\,dt \tag{2}$$

where T is the time period of the current waveform. The RMS current density is defined over T as:

$$j_{rms} = \sqrt{\frac{1}{T}\int_0^T j^2(t)\,dt} \tag{3}$$

SUMMARY

Disclosed embodiments recognize the temperature reached due to Joule heating in electrical conductor lines is not only a function of peak current (I_{peak}) and area of the line, but also the width of the current waveform (on-time), particularly for waveform (e.g., pulse) widths on the order of 100s of nsecs. The Joule heat-up (and cool down) effect for conductor lines (e.g., of an interconnect layer) takes time for the maximum temperature (and minimum temperature when cooling) to be reached as compared to the faster electrical current rise time. Thus, disclosed embodiments recognize for a given I_{peak}, the maximum temperature reached due to Joule heating is also a function of the current waveform width (on-time). Therefore, a conventional constant jpeak specification will generally be too conservative for short waveform widths unnecessarily limiting current density and thus the circuit speed or circuit density, while being too aggressive for long waveforms thus risking not guaranteeing sufficient reliability, including risking unwanted melting failures in the integrated circuit (IC).

BRIEF DESCRIPTION OF THE DRAWINGS

Reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, wherein:

FIG. **1**A is a flow chart that shows steps in an example method of computing a peak current density specification ($j_{peakspec}$) for a conductor line responsive to a current pulse using a modeling equation that includes the on-time (t_{on}) of the current waveform and a thermal time constant (τ) for the conductor line, according to an example embodiment.

FIGS. **1**B and **1**C show how t_{on} is calculated for a single current waveform pulse and for a plurality of closely spaced sub-waveform pulses which may be treated as a single current waveform, respectively, according to example embodiments.

FIG. **2** is a flow diagram for an example method of checking the jpeak for conductor lines in ICs using a disclosed $J_{peakspec}$ utilizing an equation that includes t_{on} and τ, according to an example embodiment.

FIGS. **3**A and **3**B show modeled parameters and the generation of a new $J_{peakspec}$ for a metal interconnect line, respectively, according to example embodiments.

DETAILED DESCRIPTION

Example embodiments are described with reference to the drawings, wherein like reference numerals are used to designate similar or equivalent elements. Illustrated ordering of acts or events should not be considered as limiting, as some acts or events may occur in different order and/or concurrently with other acts or events. Furthermore, some illustrated acts or events may not be required to implement a methodology in accordance with this disclosure.

FIG. **1**A is a flow chart that shows steps in an example method **100** of computing a $j_{peakspec}$ for an electrical conductor line in an IC responsive to a current waveform, where the modeling equation utilizes the t_{on} of the current waveform, according to an example embodiment. The electrical conductor line can comprise a metal interconnect line (e.g., copper line), a doped polysilicon line, or a thin film resistor (e.g., SiCr). Step **101** comprises identifying t_{on} including a full or partial on-time duration for the current waveform.

The t_{on} value is generally based on the duration of time while the current waveform is ≥a predetermined non-zero current density. When the waveform includes multiple sub-waveforms all spaced within a predetermined time range, such as from 0.001τ to 10τ, t_{on} can be calculated between the beginning and ending sub-waveforms at the predetermined current density (See FIG. **1**C described below).

Step **102** comprises computing the $j_{peakspec}$ for the electrical conductor line using a j_{peak} modeling equation which includes the t_{on} for the current waveform and τ for the electrical conductor line. For example, Equation 7 described below may be used.

Step **103** comprises checking (comparing) the peak current density j_{peak} for the electrical conductor line in an IC (e.g., obtained by a Simulation Program with Integrated Circuit Emphasis (SPICE) simulation) using the $j_{peakspec}$ determined in step **102**. Redesign of the electrical conductor line may follow based on the checking. For example, the electrical conductor line may be widened if the jpeak of the current waveform is above a predetermined level (e.g., 0.9 $j_{peakspec}$), and optionally narrowed if the jpeak of the waveform is below a predetermined level (e.g., 0.7 $j_{peakspec}$).

The modeling equation may utilize Equation 7 shown below, which can be derived starting with Equations 4 and 5 as described below. Equation 4 represents the transient temperature (T) response of the electrical conductor line due to Joule heating as a function of t_{on} and τ for a rectangular pulse, where τ is the thermal time constant which relates to the heat up or cool down rate of the electrical conductor line based on its thermal resistance to its heat sink(s). Equation 5 represents the steady state T reached by the electrical conductor line due to Joule heating for a given jpeak, dT_{ref} in (5) is a reference temperature increase, and j_{rmsref} is a reference root mean square (rms) current density which generates the dT_{ref}:

$$dT = dT_{DC}\left[1 - \exp\left(-\frac{t_{on}}{\tau}\right)\right] \tag{4}$$

$$dT_{DC.for.a.peak} = \left(\frac{j_{peak}}{j_{rms.ref}}\right)^2 dT_{ref} \tag{5}$$

Insert 5 to 4 and replace dT by dT_{spec} which is the Joule heating (JH) limit (specification) for a peak yields equation (6) below:

$$dT_{spec} = \left(\frac{j_{peakspec}}{j_{rmsref}}\right)^2 dT_{ref}\left[1 - \exp\left(-\frac{t_{on}}{\tau}\right)\right] \tag{6}$$

j_{rmsref}/dT_{ref} are constants, where dT_{ref} may be 25° C., and j_{rmsref} is a constant based on a given structure (e.g., metal interconnect stack including interlevel dielectrics). Solving (6) for $j_{peakspec}$ yields Equation (7) shown below.

$$j_{peakspec} = j_{rmsref}\left[\frac{dT_{spec}}{dT_{ref}}\frac{1}{\left[1 - \exp\left(-\frac{t_{on}}{\tau}\right)\right]}\right]^{\frac{1}{2}} \tag{7}$$

Although Equation 7 provides a particular $j_{peakspec}$ equation, other equations may be used in place of Equations 4 and 5 to derive alternatives to Equations 6, 7. Alternatives to Equations 6, 7 all include terms to account for t_{on}—for the current waveform and τ for the electrical conductor line.

FIGS. **1**B and **1**C show how t_{on} may be calculated for a single waveform pulse and for a plurality of closely spaced sub-waveform pulses which may be treated as a single waveform, respectively. FIG. **1**B shows t_{on} can include the whole pulse width where j is greater than or equal to (≥) a predetermined current density level shown as j*.

The j_{peak} value shown corresponds to the peak j. However, in another embodiment, the j_{peak} value used is averaged over specific interval within the T, such as defined between where j is greater than or equal to (≥) a predetermined current density level shown as j**; where j**>>j*, such as j*=0.1 to 10% of j_{peak}, and j**=75 to 99% of j_{peak}.

In FIG. **1**C, the current waveform shown includes multiple sub-waveforms having inter-waveform intervals having no current therebetween, where the edge-to-edge spacing of the neighboring sub-waveforms is less than or equal to (≤) 5τ, such as 2, 3, 4 or 5τ. Thus, in this embodiment, the four (4) neighboring waveforms shown as P_1, P_2, P_3 and P_4 may be considered sub-waveforms of a single current waveform, so that the t_{on} value can be considered to extend from the beginning of the first sub-waveform (e.g., from j*=0.1 to 10% of j_{peak}, such as 2% j_{peak} in one particular embodiment) to the end of the rightmost sub-waveform (e.g., at j*=0.1 to 10% of j_{peak} such as 2% j_{peak} in one particular embodiment).

In another embodiment, the j*value is obtained by reference to the $J_{peakspec}$ value, such as a j* at the beginning of the first sub-waveform at 0.1 to 10% of $j_{peakspec}$ for long t_{on}, to a j* at the end of the rightmost sub-waveform at 0.1 to 10% of $j_{peakspec}$ for long t_{on}. In one particular example, a j* value between 0.1 to 10% of jpeakspec is used for t_{on}=100τ. If t_{on}=100τ is used in Equation 7, the exponential term will be e^{-100} (equal to essentially zero), so that the jpeakspec for a long t_{on} such as 100τ is obtained where the Joule heat is sufficiently saturated (thermal equilibrium). Using the jpeakspec to set j* has an advantage of having the same thermal meaning for all the electrical conductor layers, regardless of their τ value or designed j_{peak} value, but rather on the equilibrium thermal condition of the electrical conductor line or layer

FIG. **2** is a flow diagram **200** for an example method of checking the j_{peak} of conductor lines in ICs using a disclosed $J_{peakspec}$ derived from an equation that accounts for t_{on} and τ, such as equation 7 described above, according to an example embodiment. Flow diagram **200** is related to, but is more detailed, as compared to method **100** shown in FIG. **1**A. Step **201** comprises providing an on-time based $j_{peakspec}$ equation, for example, equation 7 shown above. Step **202** comprises using thermal simulation software to simulate front end of the line (FEOL)/back end of the line (BEOL) stacks to generate simulated data including thermal data, reference Joule heat, and τ. Step **203** comprises providing a peak Joule heat spec value. Step **204** comprises setting a t_{on} sensitive $j_{peakspec}$ expression value using the peak joule heat spec value and the simulated thermal data provided.

Step **205** comprises extracting current waveform data including t_{on} and jpeak for the current waveform. Current waveform data is based on an operating point which defines the current waveform that is generally customer/user specific. Step **206** comprises comparing the j_{peak} provided in step **205** to the $j_{peakspec}$ value obtained from evaluating the t_{on} sensitive $j_{peakspec}$ expression described in step **204** (moving along the curve shown in FIG. **3**B based on t_{on}) using the t_{on} value from step **205**. If |j_peak|>|j_peak_spec|, step **207** is reached comprising redesign of the electrical conductor line, such as widening of the conductor line. If $|j_{peak}| \geq |j_{peakspec}|$ step **208** is reached and the method is ended, or another conductor line on the IC is then checked.

Disclosed embodiments include machine readable storage for implementing disclosed algorithms, including generating a t_{on} sensitive $j_{peakspec}$ for an electrical conductor line of an IC resulting from conducting pulsed electrical current, including a non-transitory machine readable storage medium having $j_{peakspec}$ generating code coded as a set of instructions stored

therein. The non-transitory machine readable storage medium can include, for example, static random access memory (SRAM), read-only memory (ROM), and/or a program storage device.

EXAMPLES

Disclosed embodiments are further illustrated by the following specific Examples, which should not be construed as limiting the scope or content of this Disclosure in any way.

FIGS. **3**A and **3**B show modeled (simulated) thermal parameters (corresponding to the output from step **202**) and the generation of a new $J_{peakspec}$ for a metal layer, respectively. Modeled τ, j_{rmsref} and dT_{ref}, are shown for M1-M5. The j_{rmsref} depends on the layer position. The dT_{spec} was set to 50° C. In FIG. **3**B, a t_{on} based jpeakspec is shown provided, with more relaxed rules for $j_{peakspec}$ for short pulses (e.g., t_{on}<0.1 time unit) and a tighter $j_{peakspec}$ shown to improve reliability for long pulses (e.g., t_{on}>6 time units) compared to a conventional $j_{peakspec}$ that is independent of t_{on}.

Disclosed embodiments can be used to aid IC design with processes which form semiconductor die that may be integrated into a variety of assembly flows to form a variety of different devices and related products. The semiconductor die may include various elements therein and/or layers thereon, including barrier layers, dielectric layers, device structures, active elements and passive elements including source regions, drain regions, bit lines, bases, emitters, collectors, conductive lines, conductive vias, etc. Moreover, the semiconductor die can be formed from a variety of processes including bipolar, CMOS, BiCMOS and MEMS.

Those skilled in the art to which this disclosure relates will appreciate that many other embodiments and variations of embodiments are possible within the scope of the claimed invention, and further additions, deletions, substitutions and modifications may be made to the described embodiments without departing from the scope of this disclosure.

The invention claimed is:

1. Machine readable storage for generating an on-time (t_{on}) sensitive peak current density specification ($j_{peakspec}$) for an electrical conductor line of an integrated circuit (IC) resulting from conducting pulsed electrical current represented as a current waveform, comprising:

a non-transitory machine readable storage medium having $j_{peakspec}$ generating code stored therein, said $j_{peakspec}$ generating code including;

code for identifying said on-time (t_{on}) for said current waveform based on a current density being greater than or equal to (≥) a predetermined current density level, and

code for computing said $j_{peakspec}$ for said electrical conductor line using a $j_{peakspec}$ modeling equation which includes said t_{on} for said current waveform and a thermal time constant (τ) for said electrical conductor line; wherein said $J_{peakspec}$ modeling equation comprises:

$$j_{peakspec} = j_{rmsref}\left[\frac{dT_{spec}}{dT_{ref}}\frac{1}{\left[1-\exp\left(-\frac{t_{on}}{\tau}\right)\right]}\right]^{\frac{1}{2}}$$

wherein:

dT_{spec} is an allowed peak temperature increase;

dT_{ref} is a reference temperature increase,

j_{rmsref} is a reference root mean square (rms) current density which generates said dT_{ref}, and

τ is said thermal time constant.

2. The machine readable storage of claim **1**, wherein said current waveform includes multiple sub-waveforms having inter-waveform intervals having no current therebetween calculated between a beginning and ending sub-waveform at said predetermined current density level.

3. The machine readable storage of claim **2**, wherein an edge-to-edge spacing of neighboring ones of said multiple sub-waveforms is less than or equal to (≤) 5τ.

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